Available online at www.sciencedirect.com
ScienceDirect
International Journal of Refrigeration 30 (2007) 1195−1206
REVUE INTERNATIONALE DU FROID
INTERNATIONAL JOURNAL OF
refrigeration
www.elsevier.com/locate/ijrefrig

Performance evaluation of a CO_2 heat pump system for fuel cell vehicles considering the heat exchanger arrangements

Sung Chul Kim[a], Min Soo Kim[a,*,1], In Chul Hwang[b], Tae Won Lim[b]

[a]School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Republic of Korea
[b]Corporate Research and Development Division, Hyundai-Kia Motors, Gyeonggi-Do 449-912, Republic of Korea

Received 1 September 2006; received in revised form 20 February 2007; accepted 20 February 2007
Available online 25 February 2007

Abstract

A novel CO_2 heat pump system was provided for use in fuel cell vehicles, when considering the heat exchanger arrangements. This cycle which had an inverter-controlled, electricity-driven compressor was applied to the automotive heat pump system for both cooling and heating. The cooling and heating loops consisted of a semi-hermetic compressor, supercritical pressure microchannel heat exchangers (a gas cooler and a cabin heater), a microchannel evaporator, an internal heat exchanger, an expansion valve and an accumulator. The performance characteristics of the CO_2 heat pump system for fuel cell vehicles were analyzed by experiments. Results for steady and transient state performance were provided for various operating conditions. Furthermore, experiments to examine the arrangements of a radiator and an outdoor heat exchanger were carried out by changing their positions for both cooling and heating conditions. The arrangements of the radiator and the outdoor heat exchanger were tested to quantify cooling/heating effectiveness and mutual interference. The improvement of heating capacity and coefficient of performance (COP) of the CO_2 heat pump system was up to 54% and 22%, respectively, when using preheated air through the radiator instead of cold ambient air. However, the cooling capacity quite decreased by 40−60% and the COP fairly decreased by 43−65%, for the new radiator-front arrangement.

Keywords: Heat pump; Automobile; Fuel cell; CO_2; R744; Transcritical cycle; Enhancement; Heat exchanger; Experiment; Steady state; Transient; Performance; COP

Evaluation de la performance d'un système à pompe à chaleur au CO_2 pour les véhicules à pile à combustible tenant compte des dispositions des échangeurs de chaleur

Mots clés : Pompe à chaleur ; Automobile ; Pile à combustible ; CO_2 ; R744 ; Cycle transcritique ; Amélioration ; Échangeur de chaleur ; Expérimentation ; Régime permanent ; Régime transitoire ; Performance ; COP

* Corresponding author. Tel.: +82 2 880 8362; fax: +82 2 883 0179.
E-mail address: minskim@snu.ac.kr (M.S. Kim).
[1] Associate Member of IIR.

0140-7007/$35.00 © 2007 Elsevier Ltd and IIR. All rights reserved.
doi:10.1016/j.ijrefrig.2007.02.008

Nomenclature

COP	coefficient of performance
C_p	specific heat (kJ kg^{-1} K^{-1})
h	enthalpy (kJ kg^{-1})
h_{fg}	evaporating enthalpy of moist air (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg h^{-1})
P	pressure (MPa)
ΔP	differential pressure (kPa)
$\dot{Q}$	heat capacity (kW)
RH	relative humidity (%)
T	temperature (°C)
$\dot{V}$	volume flow rate (m^3 min^{-1})
v	air speed (m s^{-1})
W	humidity ratio (kg H_2O (kg DA)$^{-1}$)
$\dot{W}$	compressor power (kW)

Subscripts

a	air
c	coolant
ch	cabin heater
e	evaporator
i	inlet
ind	indoor
l	latent
o	outlet
out	outdoor
r	refrigerant
rad	radiator
s	sensible

1. Introduction

Environmental concerns such as ozone depletion and global warming have been growing in recent years. R134a is not a perfect solution as an automotive representative refrigerant, because it causes global warming. On the other hand, the global warming potential (GWP) of CO_2 refrigerant is 1/1300 times lower than that of R134a. Furthermore, the size and weight of CO_2 automotive air conditioning system can decrease because CO_2 can operate at high pressure with increased volumetric refrigeration capacity.

Nowadays some studies on the CO_2 automotive air conditioning system have demonstrated that the system could provide the performance level of the conventional R134a system [1–4]. The reason is that the two systems are not equivalent with different components. For the CO_2 automotive air conditioning system, the use of an internal heat exchanger and microchannel heat exchangers is the most obvious difference, and higher compressor efficiency is also a very significant difference [3,5,6].

Based on the automotive air conditioning system, the heat pump system mainly used in electric, hybrid and fuel cell vehicles as well as high efficiency diesel engines has been developed. This system can handle the increasing need for supplementary heating for cold seasons. The heat pump system must be efficiently utilized for the cabin heating of fuel cell vehicles in the absence of exhaust heat source of relatively high temperature as in internal combustion engines. In internal combustion engine vehicles, since the compressor is a belt-driven device coupled to the engine crank shaft, its cycling rate is directly related to the vehicle speed. The losses of the heat pump system increase with elevated vehicle speed, and thus with high compressor cycling. However, the compressor used in the heat pump system for fuel cell vehicles is an electricity-driven compressor, and thus the speed of electricity-driven compressor can be adjusted independently of the vehicle speed to meet the cooling and heating loads.

The CO_2 heat pump system for both cooling and heating in the cabin of fuel cell vehicles has to be designed in relation to the heat release of a fuel cell stack. The heat pump system for heating is operated considering the exhaust heat from the fuel cell stack. Also, the heat pump system for cooling should be dealt with considering the stack cooling system with the radiator, because there is a close interaction between their heat exchangers (a radiator and a gas cooler). The issue of heat release in the stack has been known as one of the show-stoppers for the development of fuel cell vehicles. A PEM fuel cell system of 50 kW electric output with energy conversion efficiency of 50% is dumping the heat of 50 kW that must be removed from the stack in order that the stack can operate at proper reaction temperature. Therefore, if utilization of the exhaust heat is well devised, the fuel cell system will be more effective [7]. For both the heat pump system and stack cooling system, it is very important to manage and make maximum use of the exhaust heat from the fuel cell stack.

In this study, the test results are shown for the cooling performance of the CO_2 heat pump system obtained under various operating conditions at steady and transient states. Also, the experiments for examining the placement of exterior heat exchangers are carried out by changing their positions for both cooling and heating in the cabin.

2. Test facility and data analysis

The CO_2 heat pump system with novel design was provided for use in fuel cell vehicles considering the heat exchanger arrangements. Fig. 1 shows the layout of the test facility of the CO_2 heat pump system. The refrigerant loop consisted of an inverter-controlled, electricity-driven compressor, supercritical pressure microchannel heat exchangers (a gas cooler and a cabin heater), a microchannel evaporator, an internal heat exchanger, an expansion valve and an accumulator. The CO_2 compressor is a semi-hermetic